ADA

LUBRICITY DOSER EVALUATION STUDIES ON HIGH PRESSURE COMMON RAIL FUEL SYSTEM

INTERIM REPORT
TFLRF No. 447

by

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U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

for

Patsy A. Muzzell
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD17 Task 8)

UNCLASSIFIED: Distribution Statement A. Approved for public release

May 2014

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14. ABSTRACT A series of tests were conducted to evaluate the impact of a slow-release lubricity dosing filter for equipment protection and storage stability. The hardware system used for testing was a high-pressure common rail system found on John Deere 4.5L Powertech Engines. The completion of a modified test protocol based on the NATO test cycle was set as the passing criterion at 60 ^oC, 82.8 ^oC, and 93.3 ^oC. These results were compared to the results from WD 04 (Task XIX) at similar temperatures, where in the fuels were treated in bulk with DCI-4A. Based on this criterion, the dosing filter was effective in improving the performance of Jet A at 82.8 ^oC, and 93.3 ^oC. It was ineffective in improving the performance for SPK at any temperature. The performance of the dosing filter was comparable to direct DCI-4A treatment for 50/50 Jet A/SPK fuel blend. HRD fuel passed the test cycle without the lubricity additive doser at all test temperatures.			
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EXECUTIVE SUMMARY

Military ground vehicles use fuel-lubricated injection pumps to obtain acceptable performance and the bulk fuel is treated with additives, such as DCI-4A, to improve lubricity. The objective of this project was to evaluate the effectiveness of a lubricity additive dosing filter and compare it to the effectiveness of bulk treatment of the fuel. A modified test protocol based on the NATO 400-hour test cycle was adopted for this project. The completion of this test cycle using a HPCR fuel pump was set as the passing criterion at 60 ºC, 82.8 ºC, and 93.3 ºC. These results were compared to the results of the test cycle, at similar temperatures, where the fuels were treated in bulk with DCI-4A. When the additive is applied at point-of-use, rather than to bulk fuel quantities, there could potentially be financial savings associated with lower additive costs.

The dosing filter for the program was manufactured by Fleetguard and contains a slow-release lubricity additive. Equipment compatibility was conducted using a High Pressure Common Rail (HPCR) fuel system found on a John Deere 4.5L PowetechPlus engine. The three fuels that were tested on the HPCR test rig with the dosing filter and the respective test temperatures are: Jet A, Fischer-Tropsch Synthetic Paraffinic Kerosene (SPK), and 50/50 Jet A/SPK blend. In addition to the above fuels, Jet A and Hydro-treated Renewable Diesel with no lubricity doser were tested. The three temperatures used for testing were 60 ºC, 82.8 ºC, and 93.3 ºC. These temperatures were based upon previous work conducted with this fuel system, under WD 4 (Task 19), to help comparison between previous and current tests. There was no apparent difference in component wear observed for the 82.8 ºC test, for the blend treated at max DCI-4A versus the blend with the use of dosing filter. It is concluded that the effect of lubricity additive dosing filter is comparable to DCI-4A treat rates and that neither method can improve the performance of the fuel blend at 93.3 °C.

The dosing filter was effective in improving the performance of Jet A in a HPCR system by enabling completion of the entire 400 hour test at 82.8 ºC and 93.3 ºC. Jet A fuel without the dosing filter and no lubricity additive treatment was able to complete the 400 hour test only at 60 ºC. Jet A treated with 9ppm of DCI-4A was able to complete the 400 hour test for all three test temperatures. The fuel passed all three test temperatures, when a

lubricity dosing filter was used, implying that the lubricity doser had the same level of performance of DCI-4A at a minimum treat rate (9 ppm). In terms of component compatibility, when the test results were considered along with the previous data for system tests that used fuel additized at 9 ppm with DCI-4A, it was concluded that the additive and dosing filter both have a comparable and positive impact on system durability with the fuel. SPK fuel treated with 9 ppm of DCI-4A and no lubricity additive dosing filter, completed the 400 hour test cycle at 60 ºC, while it failed at 93.3 ºC with a run time of 4 hours. Clay treated SPK fuel, with the use of a lubricity additive dosing filter, failed the test cycle at 60 ºC. It was concluded that the lubricity additive dosing filter was ineffective in improving the performance of SPK fuel and that the fuel would fail further test cycles at elevated temperatures.

In the absence of a lubricity dosing filter, the fuel blend containing 50/50 Jet A/SPK blend passed the test cycle with a minimum treat rate (9 ppm) at 60 ºC and a maximum treat rate (22.5 ppm) at 82.8 ºC, while the fuel blend failed the test at 93.3 ºC at both minimum and maximum treat rates. When a lubricity dosing filter was implemented, the fuel blend passed the test cycle at 60 ºC and 82.8 ºC, while it failed at 93.3 ºC. Therefore, it was concluded that the effect of lubricity additive dosing filter was comparable to DCI-4A treat rates and that neither method could have improved the performance of the fuel blend at 93.3 ºC. It was also concluded that the performance of the SPK blend with dosing filter was improved by blending Jet A with SPK at 60 ºC and 82.8 ºC. However, blending Jet A with SPK was not sufficient to pass the cycle test run at 93.3 ºC. The test cycle at 93.3 ºC resulted in failure of the pump, with the remaining lower temperatures being able to complete the full 400 hour cycle. While the test at 82.8 ºC completed the 400 hour test, based on component evaluations, there were signs that continued use of the fuel may have resulted in pump failure. HRD fuel passed the test cycle at 82.8 ºC and 93.3 ºC, without the dosing filter leading to the conclusion that the performance of HRD fuel without the dosing filter was comparable to the performance of Jet A fuel with the dosing filter and was most definitely superior compared to the performance of Jet A without the dosing filter and 50/50 Jet A/SPK blend with the dosing filter. The higher viscosity of the HRD fuel may be a factor affecting HPCR pump wear performance compared to Jet A and SPK blend fuels.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas, performed this work during the period June 2011 through May 2014 under Contract No. W56HZV-09-C-0100. The U.S. Army Tank Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Eric Sattler (RDTA-SIE-ES-FPT) served as the TARDEC contracting officer's technical representative. Ms. Patsy A. Muzzell of TARDEC served as project technical monitor.

The authors would like to acknowledge the contribution of the TFLRF technical and administrative support staff.

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ACRONYMS AND ABBREVIATIONS

%	Percent
ASTM	American Society for Testing and Materials
BOCLE	Ball-On-Cylinder Lubricity Evaluator
cSt	CentiStoke
CI/LI	Corrosion Inhibitor/Lubricity Improver
˚C	Degrees Centigrade
˚F	Degrees Fahrenheit
HFRR	High Frequency Reciprocating Rig
HPCR	High Pressure Common Rail
JD	John Deere
kW	Kilowatt
mm	Millimeter
NATO	North Atlantic Treaty Organization
ppm	Parts per million
psi	Pounds per square inch
RPM	Revolutions per minute
SwRI	Southwest Research Institute
SPK	Synthetic paraffinic kerosene
TARDEC	Tank Automotive Research, Development and Engineering Center
TFLRF	TARDEC Fuels and Lubricants Research Facility
WSD	Wear Scar Diameter

1.0 INTRODUCTION AND OBJECTIVE

The impact of aviation fuels on military ground vehicle equipment has historically been an area of interest for the US Army. Fuel properties, which are of concern in reciprocating engines, may not matter to aviation turbine operation due to differences in application and engine design. From a logistical and financial standpoint, the use of jet fuel in the military ground fleet is desirable as long as equipment damage is prevented. One physical property of interest is lubricity of the fuel. Many ground vehicles utilize fuel-lubricated injection pumps, requiring the fuel to take on a dual role. To obtain acceptable performance, the military uses lubricity improver additives which are typically applied to the bulk fuel batch. The objective of this project was to evaluate the effectiveness of a lubricity additive dosing filter. When the additive was applied at point-of-use rather than to the bulk quantities, there could potentially be financial savings associated with lower additive costs.

2.0 LUBRICITY ADDITIVE DOSING FILTER

The dosing filter for the program was manufactured by Fleetguard and contains a slow-release lubricity additive [1][2][3]. The dosing cup coupled with a filter media is shown in Figure 1.

Figure 1. Lubricity Dosing Cup

The additive was offered in three filter options for different flow rates and filtration size requirements. Two options contained the additive in liquid form, while the third option held the additive in a waxy substrate for slow release. All three options were registered under the same EPA diesel fuel additive code.

The lubricity additive dosing filter manufacturer has reported on additive release rate [1]. The lubricity additive release rate was similar in Jet A, US and Japanese Kerosene and US DF2. The release rate increased linearly with increasing temperatures up to 140 °F. As the fuel passed over the waxy barrier, as seen on the top of the cup in Figure 1, some of the fluid passed through and displaced the additive within the doser.

Fluid exited the cup through the center hole visible on the top of the middle cone. Under normal operation, as the concentration of the additive within the cup was reduced, the viscosity of the fluid within the cup also decreased and allowed for a faster dispersion into the fuel flow path. Installation was accomplished using a standard spin-on filter head that was intended for mounting on a vehicle frame rail or other non-engine mounted location. Cummins had reported that the additive release rate during a fluid evaluation was linear from the start of test to 500 hours with approximately 30% of additive remaining at 500 hours [2].

While it was desirable to directly measure and track the concentration of the lubricity dosing additive in various fuels, it was found that the compound was a long-chain acid molecule (very similar to DCI-4A) which was not easily distinguishable from various hydrocarbons found in fuels. Therefore, in place of a direct measurement method, the additive DCI-4A was dissolved at various concentration levels in representative fuels and run through standard lubricity tests to develop a lubricity response versus additive concentration plot. Fuels were tested at 0 ppm, 9 ppm (minimum effective treat rate), 22 ppm (maximum effective treat rate), 45 ppm, 100 ppm, and 200 ppm. Results for ASTM D5001 BOCLE are shown in Figure 2.

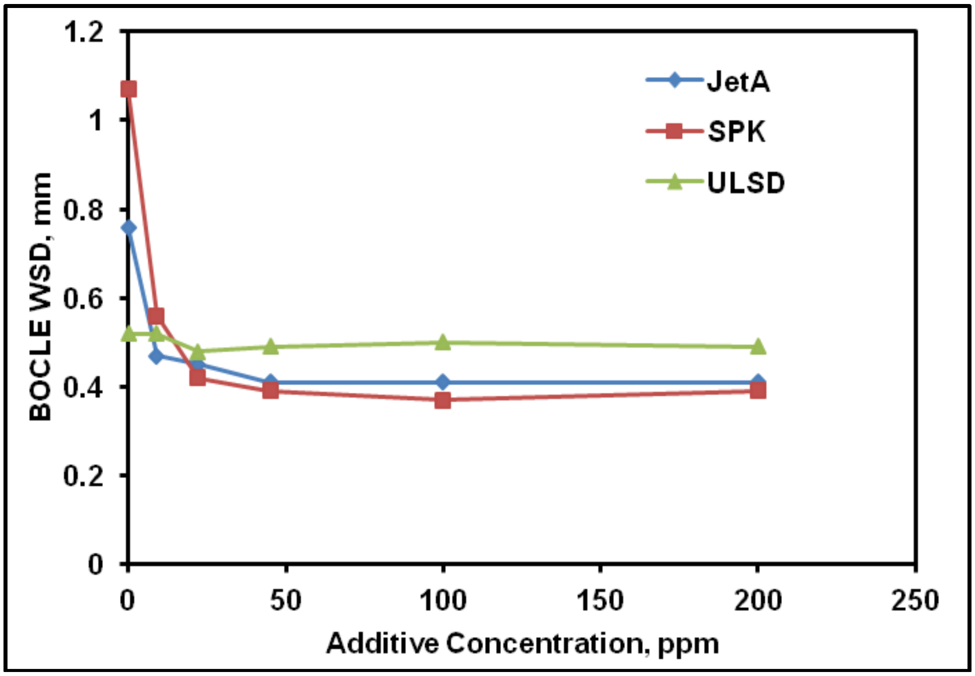

Figure 2. BOCLE Response to Additive Concentration

The BOCLE test method showed a noticeable response to the addition of the additive over small treat rates in the Jet A and SPK fuels. The ULSD fuel had very little change in the value of Wear Scar Diameter (WSD), changing from 0.52 mm at no additive concentration to 0.49 mm at the maximum treat rate of 22 ppm. This change in WSD value was within the repeatability of the test and therefore, ULSD is considered to have no response to lubricity additive. It should be noted that the response for all the fuels beyond the maximum effective treat rate was not significant. Results for ASTM D6079 HFRR for all the three fuels are shown in Figure 3.

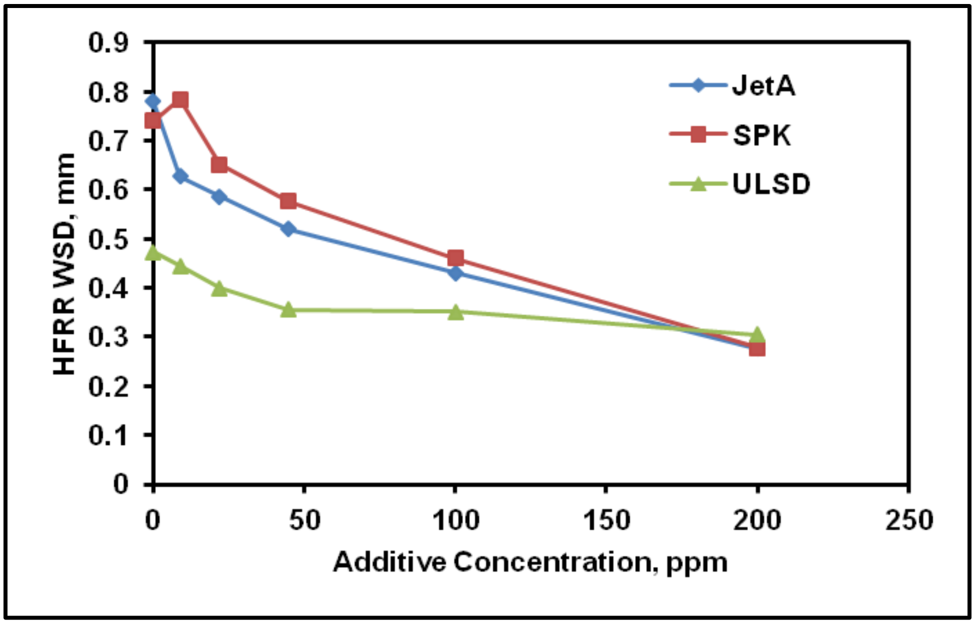

Figure 3. HFRR Response to Additive Concentration

All three test fuels had a broader response for the HFRR test compared to the BOCLE lubricity test. The WSD for Jet A and SPK fuels continued to decrease beyond the maximum treat rate (22 ppm) and had shown response up to 200 ppm treat rate. The HFRR WSD for ULSD fuel had shown a good response up to a treat rate of 45 ppm, beyond which the change in WSD remained insignificant. Therefore, the response of ULSD to HFRR was significant for a maximum additive concentration of 45 ppm.

The use of WSD by either method did not exhibit enough sensitivity to be used as an indirect method for determining additive concentration released from the doser filter.

3.0 LONG TERM FUEL STORAGE STABILITY STUDY

A brief investigation was conducted to determine the effect of static storage stability on the doser filter. The long term storage stability of fuels in the dosing filter was evaluated by using eight dosing filters filled with fuel. Four were tested with clay treated Jet A and four with clay treated 50/50 blend of Jet A and SPK. The storage test was conducted for a six month period at a

temperature of 60 °C. Each filter was stored upright in a sealed container to prevent the loss of fluid due to evaporation. At the end of the testing period, all the filters were removed and drained to capture the resulting fuel for testing. The cup containing the additive from within the filter was also removed and drained. The clean fuel that had gone into the filter was brown in color upon removal. Figure 4 shows the fuel from one such dosing filter tested with Jet A.

Figure 4. Storage Stability Test – End-Of-Test Fluid, Jet A in Filter No. 4

The level of additive in the filter and the density values were measured for each fluid from the storage stability tests as well as the neat fuels and additive fluid. Based on these values, an approximate concentration of the additive in the dosing cup was determined in each filter as shown in Table 1.

Table 1. Storage Stability Test Data – Density and Percent Additive Remaining

Sample (All density data from D4052 at 15 ºC)		Density (g/cm^3)	Percent Additive Remaining (%)
Neat Additive		0.8759	100.0
Jet A (Base Fuel ρ = 0.7628 g/cm^3)	Filter Cup 1	0.8305	59.9
	Filter Cup 2	0.8349	63.7
	Filter Cup 3	0.8370	65.6
	Filter Cup 4	0.8279	57.6
Blend (Base Fuel ρ = 0.7473 g/cm^3)	Filter Cup 1	0.8229	58.8
	Filter Cup 2	0.8265	61.6
	Filter Cup 3	0.8279	62.7
	Filter Cup 4	0.8164	53.7

Based upon this study, it could be estimated that a filter sitting idle on a vehicle in a motor pool, would lose a substantial amount of its additive content over time due to dilution into the surrounding fuel. While this impacts the life of the filter, by reducing the remaining additive available for dispersal, there is also an unknown impact on the engine fuel system being flooded with a large volume of highly additized fuel upon engine restart after down-time. There may be a durability benefit of flooding potentially dry components with high-lubricity fuel. There may be issues with injection and combustion that need additional investigation. The other filter concern, based upon the storage stability study, was the loss of a substantial amount of additive to fuel in an isolated, closed area. If the additive were able to disperse into the larger fuel quantity as found in an operating vehicle fuel system, a lower volume of fuel additive could be expected to remain in the cup when it came out of storage.

4.0 TEST CYCLE PERFORMANCE EVALUATION

4.1 TEST EQUIPMENT AND TEST CYCLE

Equipment compatibility was conducted using a High Pressure Common Rail (HPCR) fuel system found on John Deere 4.5L PowetechPlus engine. This system had been previously evaluated for use with various aviation fuels and synthetic fuels, creating baseline data [7] and was compared to results in the current work. The test rig is shown in Figure 5.

Figure 5. High Pressure Common Rail Test Rig

During the previous evaluation of the fuel system, it was found that the high pressure pump contained the locations that were most sensitive to fuel conditions. The central camshaft of the pump contained a ring cam on an eccentric lobe. As the shaft turned, the ring cam force opposed the plungers into the pump head to create high pressure on the fuel, as illustrated in Figure 6.

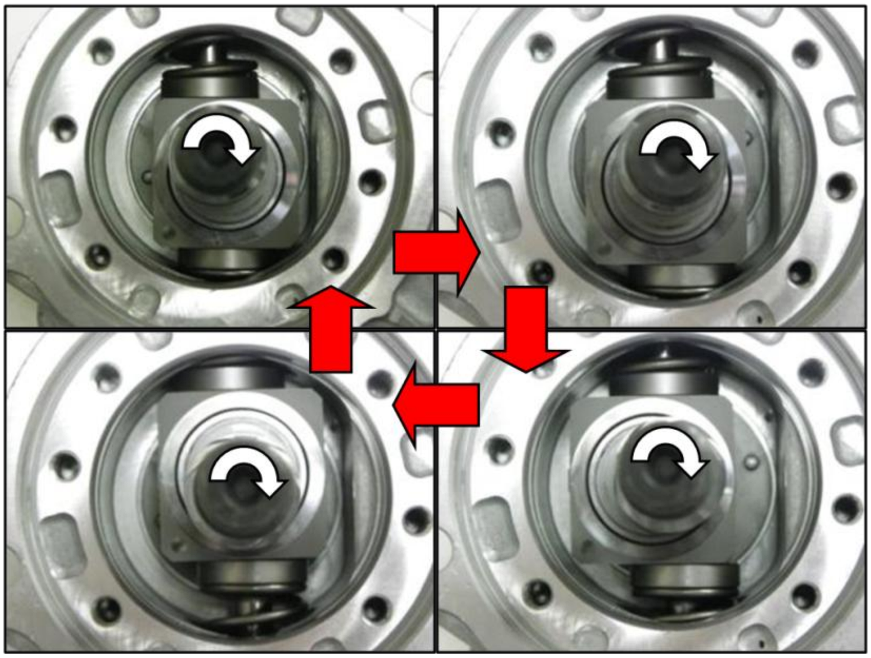

Figure 6. Rotation of Eccentric Lobe and Ring Cam within High Pressure Pump

The most common failure mode observed for the pump was seizure of the ring cam on the shaft, followed by excessive wear and breakage of the plungers.

The test stand was modified to accept a secondary fuel filter upstream of the primary filter as shown in Figure 7.

Figure 7. Dosing Filter on HPCR Test Rig

In addition to the dosing filter, a clay treatment system was installed for the injected fuel returning to the drum. This installation was to prevent the build-up of additive over time in the incoming fuel being supplied to the test stand. The test stand schematic is shown in Figure 8.

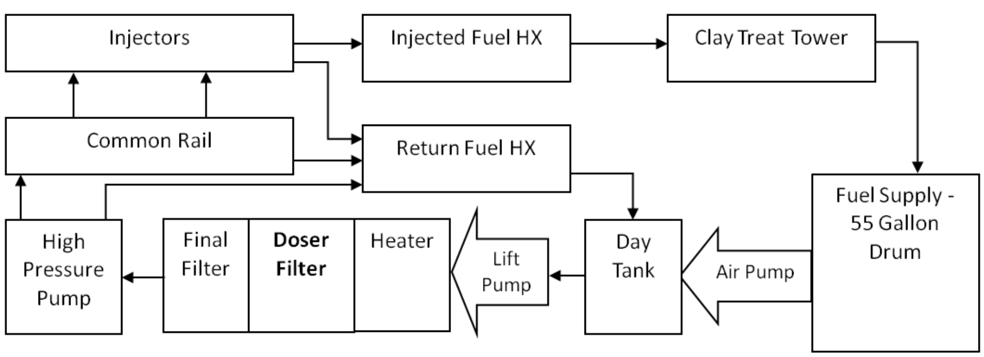

Figure 8. Pump Stand Schematic with Dosing Filter and Clay Treat Tower

The test was conducted for 400 hours of repeated 10-hour cycles. Speed and Load were controlled to the guidelines adopted from the NATO test cycle, a summary of which is given in Table 2.

Table 2. Test Cycle for John Deere HPCR Pump Stand

Step	Pump Speed (RPM)	Throttle (%)	Duration (hrs)
1	800	0	0.5
2	2400	100	2
3	2560	0	0.5
4	1800	100	1
5*	800 to 2400	0 to 100	2
6	1440	100	0.5
7	800	0	0.5
8	2500	70	0.5
9	1500	100	2
10	1440	50	0.5

*Step 5 cycles between idle and rated conditions

4.2 Test Fuels and Test Cycle Results

The three fuels that were tested on the HPCR test rig with the dosing filter and the respective test temperatures are: Jet A, Fischer-Tropsch Synthetic Paraffinic Kerosene (SPK), and 50/50 Jet A/ SPK blend. In addition to the above fuels, Jet A and Hydro-treated Renewable Diesel with no lubricity doser were tested for baseline information. The three fuel temperatures used for testing were 60 °C, 82.8 °C, and 93.3 °C.

These temperatures were based upon previous work conducted with this fuel system, under WD 4 (Task 19), to help with comparison between previous and current tests. Prior to each test, two 55-gallon drums containing the test fuel were clay treated to remove any additives. These drums were alternated between each 100 hour test segment for the entire 400 hour test cycle. A summary of the test fuels is shown in Table 3. Kinematic viscosity values from ASTM D445 [4] are listed at the fuel test temperature, while BOCLE [5] and HFRR [6] results are reported at the standard temperature listed in their respective ASTM test procedure.

Table 3. Test Fuels and Summary of Results

Fuel	Dosing Filter (Yes/No)	Temperature (°C)	Test Duration (hrs)	Kinematic Viscosity (cSt)	BOCLE WSD (mm)	HFRR WSD (mm)
Jet A	Yes	60.0	400	0.89	0.76	0.78
		93.3	400	0.65		
Jet A	No	60.0	400	0.89		
		82.8	4.00	0.71		
SPK	Yes	60.0	92.1	0.76	1.07	0.74
50/50 – Jet A/SPK Blend	Yes	60.0	400	0.82	0.84	0.76
		82.8	400	0.66		
		93.3	0.50	0.60		
HRD	No	82.8	400	1.25	0.61	0.61
		93.3	400	1.16		

The test cycle results bear the following facts and conclusions:

i. The entire test cycle (400 hours) was completed with Jet A fuel, using a dosing filter, at 60 °C and 93.3 °C. In the absence of the dosing filter, the entire 400 hour test cycle was completed, with Jet A, at 60 °C. At 82.8 °C the test ended with a duration of 4 hours. Hence, it can be concluded that the dosing filter was effective in improving the performance of Jet A in a HPCR system by enabling the completion of the entire 400 hour test at 93.3 °C.

ii. The test run with SPK fuel at 60 °C ended at 92.1 hours with the lubricity additive dosing filter. With neat SPK as the base fuel, use of the dosing filter did not enable completion of the 400 hour test.

iii. A 50/50 blend of Jet A/SPK was prepared and tested. When using the dosing filter, the 400 hour test was passed at 60 °C and 82.8 °C. Even with the doser, the Jet A/SPK blend failed the test at 93.3 °C with 0.5 hours of test run.

iv. HRD fuel completed the 400 hour test run at 82.8 °C and 93.3 °C, without the dosing filter. Thus, the level of performance of HRD fuel without the dosing filter is:

   a. Comparable to the performance of Jet A fuel with the dosing filter.

   b. Superior compared to the performance of Jet A without the dosing filter and 50/50 Jet A/SPK blend with the dosing filter.

c. The higher viscosity of the HRD fuel may be a factor affecting HPCR pump wear performance compared to Jet A and SPK blend fuels.

4.3 COMPARISON WITH TEST CYCLE RESULTS FROM WD 04 (TASK XIX)

Table 4, lists the fuels, test temperatures, lubricity additive treat rates, and test cycle durations for tests conducted using a High Pressure Common Rail (HPCR) fuel system found on John Deere 4.5L PowertechPlus engine under WD 04 (Task XIX). It should be noted that all the fuels were clay treated prior to treatment with DCI-4A.

Table 4. Test Cycle Results for Equipment Compatibility Studies in WD 04 (Task XIX) [7]*

Fuel	DCI-4A Treat rate (ppm)	Temperature (°C)	Test Duration (hrs)
Jet A	9	60.0	400
		93.3	400
SPK	9	60.0	400
		93.3	4
50/50 – Jet A/SPK Blend	9	60.0	400
	22.5	82.8	400
	9	93.3	4
	22.5	93.3	4

**No lubricity dosing filter was used for WD 04 (Task XIX).*
ULSD result is not listed in the above table, since this fuel was not tested under WD 04.

A comparison between test cycle results achieved using the dosing filter (in Table 3) and without the dosing filter (in Table 4), bears the following facts and conclusions:

i. Jet A fuel when used without the dosing filter and no lubricity additive treatment was able to complete the 400 hour test only at 60 °C. Jet A treated with 9ppm of DCI-4A was able to complete the 400 hour test for all three test temperatures. When a lubricity dosing filter was used for the test run with clay treated Jet A, the fuel passed all three test temperatures. This implies that either DCI-4A at a minimum treat rate (9 ppm) or a lubricity dosing filter is required for successful test run at 82.8 °C and 93.3 °C, for Jet A fuel.

ii. SPK fuel, at a minimum treat rate of 9 ppm with DCI-4A, and no lubricity additive dosing filter, passed the test at 60 °C and failed at 93.3 °C (4 hours). Clay treated SPK fuel failed the test at 60 °C with the use of a lubricity additive dosing filter. Hence, it can be concluded that the dosing filter was ineffective in improving the performance of SPK fuel.

iii. Fuel blend containing 50/50 Jet A/SPK passed the test run with a minimum treat rate (9 ppm) at 60 °C and a maximum treat rate (22.5 ppm) at 82.8 °C, while the fuel blend failed the test at 93.3 °C at both minimum and maximum treat rates. When a lubricity dosing filter was used, the fuel blend passed the test at 60 °C and 82.8 °C, while it failed at 93.3 °C with a run time of 0.5 hours. There was no apparent difference in component wear observed for the 82.8 °C test, for the blend treated at max DCI-4A versus the blend with the use of dosing filter. It is concluded that the effect of lubricity additive dosing filter is comparable to DCI-4A treat rates and that neither method can improve the performance of the fuel blend at 93.3 °C.

5.0 FUEL – COMPONENT COMPATIBILITY EVALUATION

5.1 IMPACT OF JET A ON COMPONENT COMPATIBILITY

The filter's impact on Jet A was of considerable value and interest due to its probable future usage in military ground vehicle applications. Previous testing had shown Jet A to provide acceptable protection to the system when treated with the minimum level, 9 ppm of lubricity improver DCI-4A up to 93.3 °C. The ring cam and plunger face interaction was examined at the end of each test for condition. Figure 9 and Figure 10 shows the upper and lower ring cam face respectively, while the upper and lower plunger face are shown in Figure 11 and Figure 12 respectively. The condition of the cam and plunger surfaces for Jet A, No doser at 82.8 °C showed a large amount of heat exposure and impact damage along the edge. Since failure occurred at four hours after test start, it was evident that the fuel system components within the pump definitely required lubricity additive for 400 hour test cycle operation with Jet A at 82.8 °C.

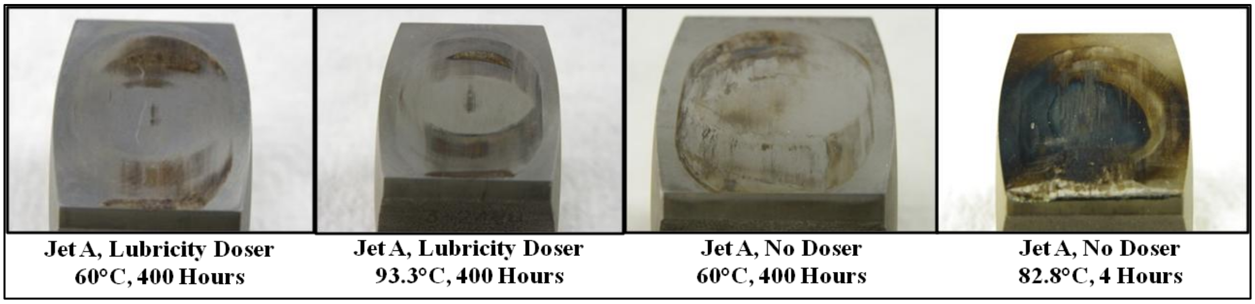

Figure 9. Jet A Component Compatibility – Upper Ring Cam Face

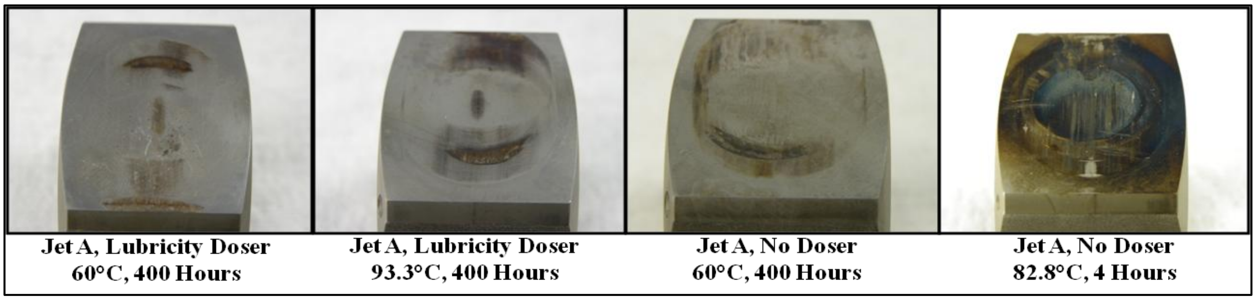

Figure 10. Jet A Component Compatibility – Lower Ring Cam Face

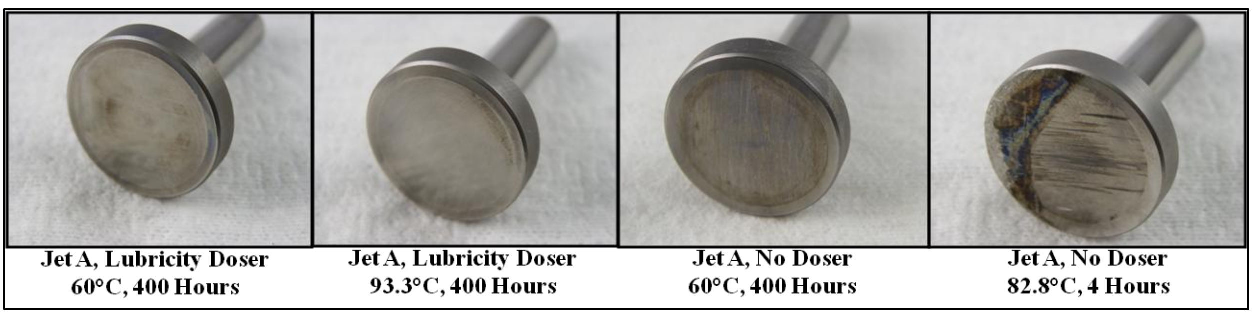

Figure 11. Jet A Component Compatibility – Upper Plunger Face

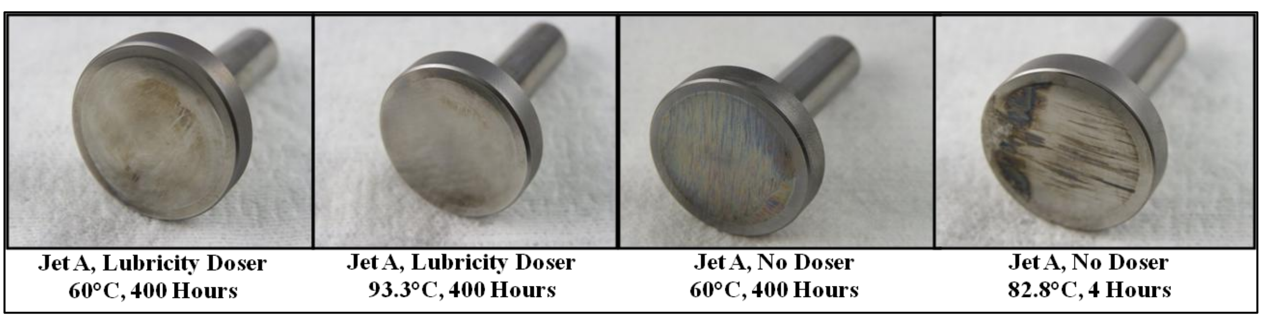

Figure 12. Jet A Component Compatibility – Lower Plunger Face

At the 60 °C and 93.3 °C tests, with the lubricity doser, the wear scars on components had a more polished appearance compared to the test at 60 °C with no dosing filter or additive. The size of the polished area was larger at the higher temperature, possibly due to the lower viscosity, but it did not show signs of deeper wear, similar to the reversal area on the unadditized test component. This indicated that the benefit of the lubricity additive was being realized primarily when there was relative motion between the components, and thus the fluid film thickness was at a minimum. Protection at this point in the revolution of the pump could be one of the more critical areas for system integrity. When the current test results were considered along with the previous data for system tests using fuel additized at 9 ppm with DCI-4A, it could be seen that the additive and dosing filter both had a comparable and a positive impact on system durability with the fuel.

5.2 IMPACT OF SPK ON COMPONENT COMPATIBILITY

SPK compatibility was only evaluated at the lowest operating test temperature, at 60 °C. Based upon previous work, it was known that the pump system was sensitive to operation with SPK at high temperature with DCI-4A additive. The test cycle at 60 °C failed, with a run time less than 100 hours. Unlike many other evaluations with this hardware set, the failure did not occur the first time through the test run. Typically, the first ramp from idle to rated load, speed, and pressure during the fifth phase had resulted in seizure of the pump. With the doser filter and SPK fuel at 60 °C, the pump was able to survive over 90 hours, well beyond the 4 hour mark but short of a complete 400 hour test.

In comparison, the same fuel treated at an additive rate of 9 ppm DCI-4A was able to complete a full 400-hour test at 60 °C, and was able to complete slightly over 4 hours at 93.3 °C. Based on these results, the dosing filter appeared to have provided insufficient protection to the fuel pump compared to the minimum level of DCI-4A additive. Upon establishing the fact that the fuel and temperature combination along with the dosing filter provided insufficient hardware protection at 60 °C, further test cycles at elevated temperatures were not conducted.

Figure 13 shows the condition of the failed upper plunger along with the lower plunger for comparison, along with the upper ring cam face and lower ring cam face. Failure occurred at the point where the wider plunger face and shaft intersect. While the shaft of the upper plunger was seized inside the pump bore, the lower shaft showed no signs of wear upon removal. The upper ring cam face and lower ring cam face show minor wear scar and impact damage.

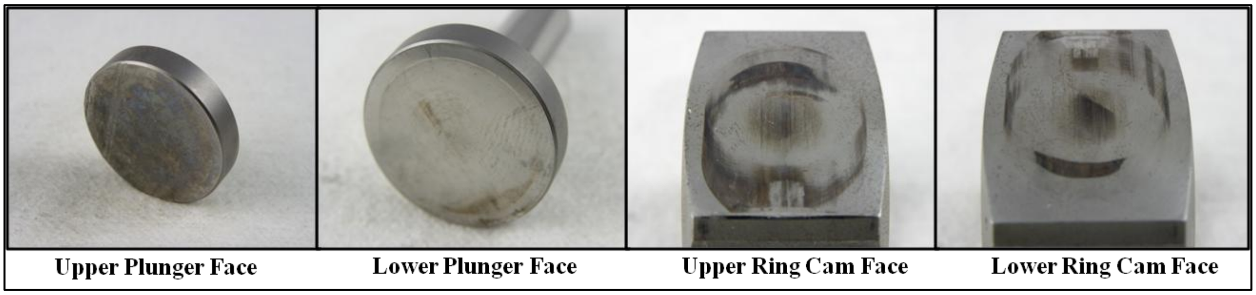

Figure 13. Plunger and Ring Cam Face – SPK Fuel with Lubricity Doser at 60 °C

Figure 14 shows the condition of other components within the pump. The initial failure occurred at the interface between the cam lobe and bushing. The lubricity and viscosity of the fuel at this location were unable to prevent contact and material transfer between the two surfaces. As the friction increased, the ring cam rotation began to stick and made side-loaded contact with the plunger face. This resulted in face snapping and plunger becoming seized inside the bore. In Figure 14, the shaft, ring cam, and bushing had to be separated using a hydraulic press.

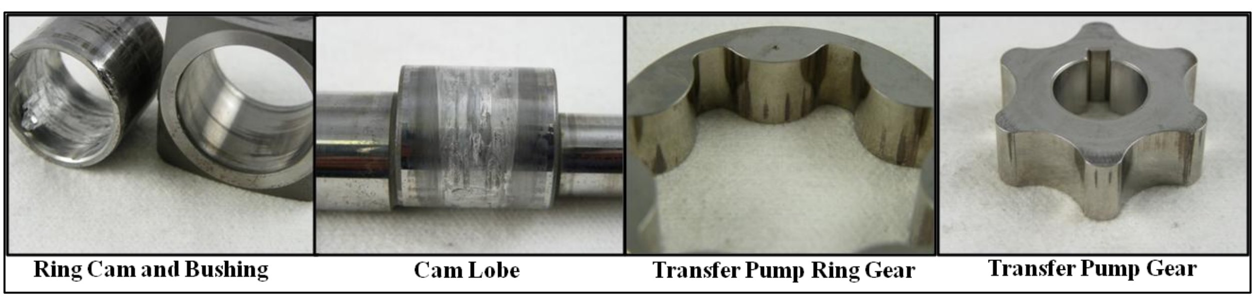

Figure 14. Component Evaluation – SPK Fuel with Lubricity Doser at 60 °C

The other two components shown were located within the transfer pump driving off of the same cam shaft. Small wear marks could be seen at the tips of the gear, but the extent of the wear was

typical of that seen in almost all other tests conducted. This particular area was low pressure and lightly loaded in comparison to the plungers and ring cam.

5.3 IMPACT OF JET A/SPK FUEL BLEND ON COMPONENT COMPATIBILITY

SPK and Jet A fuel blends (50/50) were evaluated at all three test temperatures using the doser. The test cycle at 93.9 ºC resulted in failure of the pump, with the remaining lower temperature tests being able to complete the full 400 hour cycle. While the 82.8 ºC test completed the 400 hour test, there were signs that continued use of the fuel may have resulted in pump failure.

Figure 15 shows the condition of the upper cam ring face. The upper face from the 82.8 ºC test showed very little wear compared to the evaluation at the lower temperature. Figure 16 shows very similar results to those seen on the upper ring cam face.

Figure 15. 50/50 Jet A/SPK Blend Component Compatibility – Upper Ring Cam Face

Figure 16. 50/50 Jet A/SPK Blend Component Compatibility – Lower Ring Cam Face

Figure 17 shows the upper plunger face. In contrast to the observation on ring cam, the test at 82.8 ºC showed signs of high heat and wear in a pattern that is centered on the plunger face and not across the plunger face in a normal direction of motion. Figure 18 shows the lower plunger face and had the same results as the upper plunger face. The area that appears to be exposed to high levels of heat in the 82.8 ºC test was larger than on the upper component.

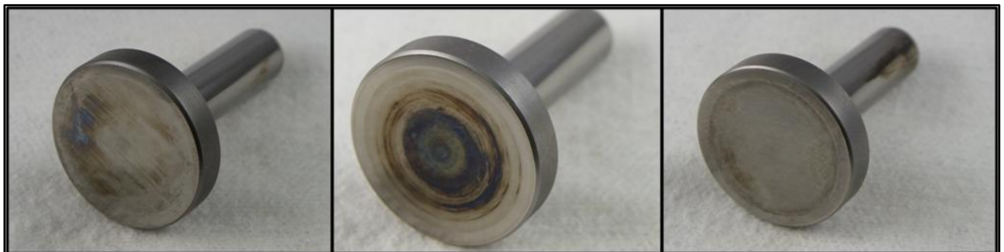

Figure 17. 50/50 Jet A/SPK Blend Component Compatibility – Upper Plunger Face

Figure 18. 50/50 Jet A/SPK Blend Component Compatibility – Lower Plunger Face

Figure 19 shows that the condition of the bushing was almost new at the end of the 400 hours test cycle that was conducted at 60 ºC. The test temperature at 82.8 ºC caused a heavy wear on the bushing material by the end of the test. At 93.3 ºC, the wear developed across the entire bushing face and resulted in high friction and seizure onto the cam lobe, during the four hours of test cycle.

Figure 19. 50/50 Jet A/SPK Blend Component Compatibility –Ring Cam Bushing

Figure 20 shows the condition of cam lobe for each of the three blended fuel tests. The highest temperature test had developed heavy scoring in a short period of time. Results showed that the blend of SPK and Jet A fuels coupled with a lubricity dosing filter could be suitable for use up to 82.8°C based on the test results.

Figure 20. 50/50 Jet A/SPK Blend Component Compatibility –Cam Lobe

While the test cycle was successfully completed for the fuel blends at two lower temperatures, based on the totality of component evaluations, we estimate a high probability that failure could have occurred if the length of the test cycle was extended beyond 400 hours.

5.4 IMPACT OF HRD ON COMPONENT COMPATIBILITY

HRD fuel completed the 400 hour test cycle at 82.8 ºC and 93.3 ºC. Figure 21 and Figure 22 compares the impact of fuel on upper plunger face, lower plunger face, upper ring cam face, and lower ring cam face respectively.

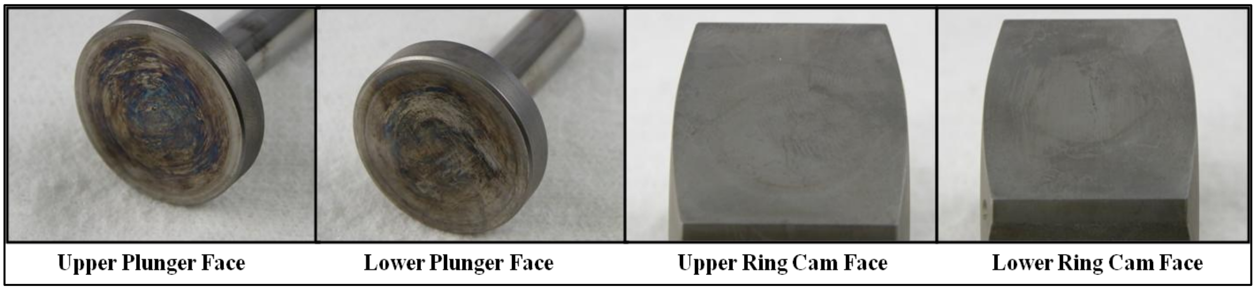

Figure 21. HRD – Component Compatibility Evaluation at 82.8 ºC, No Lubricity Doser

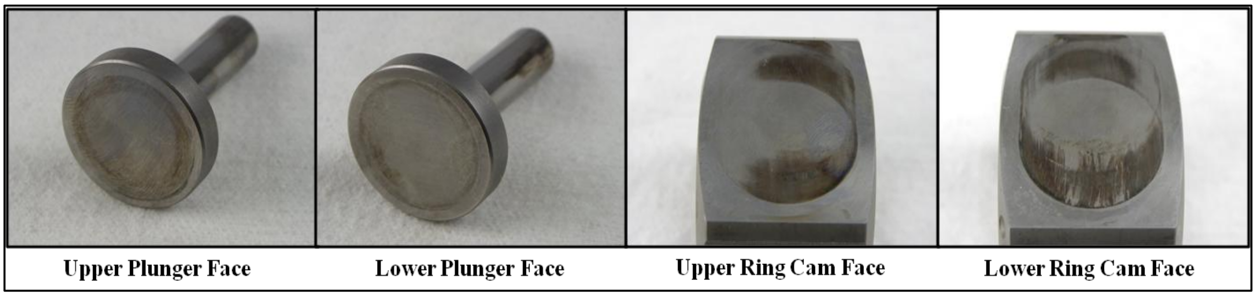

Figure 22. HRD – Component Compatibility Evaluation at 93.3 ºC, No Lubricity Doser

The upper ring cam face and lower ring cam face showed more wear at 93.3 ºC compared to 82.8 ºC. In contrast, the upper plunger face and lower plunger face showed more wear and heat damage at 82.8 ºC, compared to 93.3 ºC. Similarly, Figure 23 showed that the cam lobe has suffered more wear and damage 82.8 ºC, compared to 93.3 ºC.

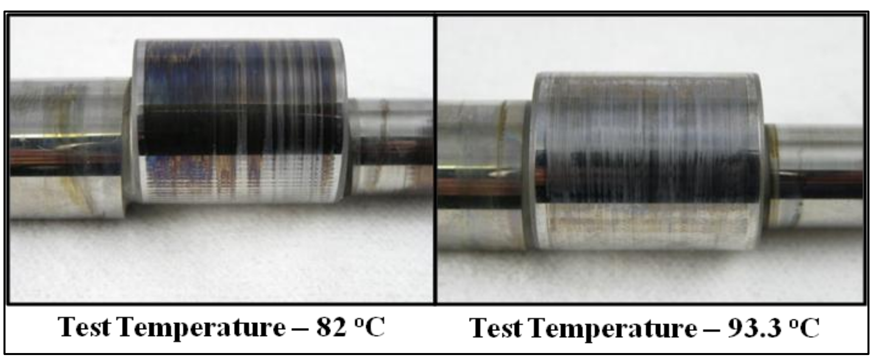

Figure 23. Cam Lobe Comparison between 82.8 ºC and 93.3 ºC – HRD, No Lubricity Doser

The test cycle performance of HRD fuel with no lubricity doser was comparable to that of Jet A with lubricity doser, as stated in section 5.2. Therefore, the lubricity doser was not a requirement based on the above conclusion. However, based on the component compatibility evaluations, it can be concluded that the level of wear with HRD fuel was much higher compared to Jet A with lubricity doser. On the basis of such conclusion, while lubricity doser might not be a requirement, it is recommended that lubricity doser could be used in future with HRD fuel with the goal of minimizing component wear.

6.0 CONCLUSIONS

The dosing filter was effective in improving the performance of Jet A in a HPCR system by enabling completion of the entire 400 hour test run at higher test temperatures, namely 82.8 ºC and 93.3 ºC. Jet A fuel without the dosing filter and no lubricity additive treatment was able to complete the 400 hour test only at 60 ºC. Jet A treated with 9 ppm of DCI-4A was able to complete the 400 hour test run for all three test temperatures. The fuel passed all three test temperatures, when a lubricity dosing filter was used, implying that the lubricity doser has at least the same level of performance of DCI-4A at a minimum treat rate (9 ppm). In terms of component compatibility, when the current test results are considered along with the previous data for system tests using fuel additized at 9 ppm with DCI-4A, it was concluded that the additive and dosing filter both have a comparable and positive impact on system durability with the fuel.

SPK fuel treated with 9 ppm of DCI-4A and no lubricity additive dosing filter, completed the 400 hour test cycle at 60 ºC and failed at 93.3 ºC with a run time of 4 hours. Clay treated SPK fuel failed the test cycle at 60 ºC with the use a lubricity additive dosing filter. It was concluded that the lubricity additive dosing filter was ineffective in improving the performance of SPK fuel. Upon establishing the fact that the fuel and temperature combination along with the dosing filter provided insufficient hardware protection at 60°C, further test cycles at elevated temperatures were not conducted.

Fuel blend containing 50/50 Jet A/SPK blend passed the test cycle with a minimum treat rate (9 ppm) at 60 ºC and a maximum treat rate (22.5 ppm) at 82.8 ºC, while the fuel blend failed the test at 93.3 ºC at both minimum and maximum treat rates (Lubricity doser was not used at the three temperatures). When a lubricity dosing filter was implemented, the fuel blend passed the test cycle at 60 ºC and 82.8 ºC, while it failed at 93.3 ºC. Therefore, it was concluded that the effect of lubricity additive dosing filter is comparable to DCI-4A treat rates and that neither method improved the performance of the fuel blend at 93.3 ºC.

HRD fuel passed the test cycle at 82.8 ºC and 93.3 ºC, without the dosing filter leading to the conclusion that of performance of HRD fuel without the dosing filter was comparable to the performance of Jet A fuel with the dosing filter and most definitely had a superior performance compared to Jet A without the dosing filter and 50/50 Jet A/SPK blend with the dosing filter. The higher viscosity of the HRD fuel may be a factor affecting HPCR pump wear performance compared to Jet A and SPK blend fuels.

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APPENDIX A.
FUEL LUBRICITY MEASUREMENTS

The lubricity values were measured for fuel samples collected from the fuel drum and from the return line sample valve on the wall. “X” indicates that data is not available. The results indicate that there were no substantial changes in lubricity values over the test duration.

Table A-1. Jet A Fuel without Lubricity Doser

Time (hrs)	BOCLE WSD (mm)				HFRR WSD (mm)			
	Test at 60 ºC		Test at 82.8 ºC		Test at 60 ºC		Test at 82.8 ºC	
	Drum	Wall	Drum	Wall	Drum	Wall	Drum	Wall
0	0.94	0.94	0.93	0.93	0.748	0.748	0.748	0.748
100	0.87	0.87	Test failed at 4 hours		0.766	0.817	Test failed at 4 hours	
200	0.89	0.89			0.804	0.787		
300	0.84	0.85			0.788	0.755		
400	0.87	0.87			0.782	0.774		

Table A-2. Jet A Fuel with Lubricity Doser

Time (hrs)	BOCLE WSD (mm)				HFRR WSD (mm)			
	Test at 60 ºC		Test at 93.3 ºC		Test at 60 ºC		Test at 93.3 ºC	
	Drum	Wall	Drum	Wall	Drum	Wall	Drum	Wall
0	0.76	0.76	X	X	0.755	0.755	0.755	0.755
100	0.79	0.74	X	X	X	0.768	X	0.755
200	0.78	0.76	X	X	X	0.768	X	0.778
300	0.79	0.77	X	X	X	0.764	X	0.723
400	0.77	0.76	X	X	0.789	0.802	X	0.781

Table A-3. SPK Fuel with Lubricity Doser

Fuel Sample Description	Test at 60 ºC; Test Failed at 92.6 hrs	
	BOCLE WSD (mm)	HFRR WSD (mm)
Sample from Drum at 0 hours	0.48	0.733
Sample from Heater at 92.6 hours	0.80	0.737
Sample from Filter at 92.6 hours	0.48	X

Table A-4. 50/50 Jet A/SPK Fuel Blend with Lubricity Doser

Time (hrs)	BOCLE WSD (mm)				HFRR WSD (mm)			
	Test at 60 ºC		Test at 82.8 ºC		Test at 60 ºC		Test at 82.8 ºC	
	Drum	Wall	Drum	Wall	Drum	Wall	Drum	Wall
0	0.87	0.82	0.93	0.93	0.803	0.784	0.809	0.809
100	X	X	0.84	0.78	X	X	0.792	0.751
200	0.88	0.82	0.81	0.75	0.798	0.758	0.779	0.747
300	0.86	0.85	0.82	0.79	0.782	0.777	0.769	0.771
400	0.90	0.85	0.86	0.86	0.762	0.741	0.775	0.796

Note: Test at 93.3 °C failed at 0.5 hours

Table A-5. HRD Fuel without Lubricity Doser

Time (hrs)	BOCLE WSD (mm)			
	Test at 82.8 ºC		Test at 93.3 ºC	
	Drum	Wall	Drum	Wall
0	0.89	0.93	0.94	0.94
100	0.71	0.60	0.80	0.81
200	0.79	0.82	0.86	0.86
300	0.77	0.79	0.79	0.77
400	0.83	0.83	0.82	0.82